A HIERARCHICAL MODEL FOR REGIONAL ANALYSIS OF POPULATION CHANGE USING CHRISTMAS BIRD COUNT DATA, WITH APPLICATION TO THE AMERICAN BLACK DUCK

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Abstract. Analysis of Christmas Bird Count (CBC) data is complicated by the need to account for variation in effort on counts and to provide summaries over large geographic regions. We describe a hierarchical model for analysis of population change using CBC data that addresses these needs. The effect of effort is modeled parametrically, with parameter values varying among strata as identically distributed random effects. Year and site effects are modeled hierarchically, accommodating large regional variation in number of samples and precision of estimates. The resulting model is complex, but a Bayesian analysis can be conducted using Markov chain Monte Carlo techniques. We analyze CBC data for American Black Ducks (*Anas rubripes*), a species of considerable management interest that has historically been monitored using winter surveys. Over the interval 1966–2003, Black Duck populations showed distinct regional patterns of population change. The patterns shown by CBC data are similar to those shown by the Midwinter Waterfowl Inventory for the United States.

Key words: Anas rubripes*, Bayesian, Christmas Bird Count, count data, hierarchical models, Markov chain Monte Carlo.*

Un Modelo Jerárquico para el Análisis Regional del Cambio Poblacional Empleando Datos de Conteos Navideños de Aves, con una Aplicación al Caso de *Anas rubripes*

Resumen. El análisis de los datos de los conteos navideños de aves es complicado por la necesidad de tener en cuenta la variación en el esfuerzo en los conteos y de proveer resúmenes a través de regiones geográficas amplias. En este estudio describimos un modelo jerárquico para analizar los cambios en las poblaciones usando datos de conteos navideños que suple esas necesidades. El efecto del esfuerzo es modelado paramétricamente, haciendo variar los valores de los parámetros entre estratos como efectos aleatorios distribuidos idénticamente. Los efectos del año y del sitio son modelados jerárquicamente, teniendo en cuenta la amplia variación regional en el número de muestras y la precisión de los estimados. El modelo resultante es complejo, pero es posible realizar un análisis Bayesiano empleando técnicas de cadenas de Markov Monte Carlo. Analizamos datos de conteos navideños para *Anas rubripes*, una especie de considerable interés desde el punto de vista de manejo que ha sido monitoreada históricamente por medio de censos durante el invierno. En el intervalo entre 1966 y 2003, las poblaciones de *A. rubripes* mostraron patrones marcados de cambio a nivel regional. Los patrones mostrados por los datos de los conteos navideños son similares a los que muestran los inventarios de aves acuáticas de mitad del invierno realizados en los Estados Unidos.

INTRODUCTION

The Audubon Christmas Bird Count (CBC) is a volunteer-based survey of early winter bird populations that was initiated in 1900 (Butcher 1990). Although primarily covering the United States and Canada, CBC methodology has been implemented worldwide, and allows many bird watchers an opportunity to contribute to a conservation activity. The survey is conducted within a few weeks of 25 December. Sample units for the survey are 24.13-km (15 mi) diameter circles. The number of counters and the methods of data collection vary among circles and through time, and changes in counts over space and time often are influenced by these methodological issues. Although the CBC has been used for scientific and conservation activities such as modeling and evaluation of ranges of birds (Bock and Root 1981, Root 1988), and estimation of population change (Sauer et al. 1996, Dunn and Sauer 1997), all analyses of the survey are limited by non-random selection of circle locations and the

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lack of standardization in counting methods. Early in the survey, a clear association was noted between counting effort and magnitude of counts; consequently during most of the 20th century information on effort expended in counting has been routinely collected for each circle (Butcher 1990). Scientific uses of the survey such as modeling and evaluation of ranges of birds (Root 1988) and estimation of population change (Sauer et al. 1996, Dunn and Sauer 1997) all have attempted to control for counting effort in analysis.

Link and Sauer (1999a, 1999b) proposed a flexible model for the effect of effort in the CBC. Their model specifies that all other things being equal, the effect of effort is to increase or decrease expected counts by a factor

$$f(\xi) = \exp(B(\xi^p - 1)/p) .$$

Here ξ is the effort value divided by the mean effort; parameters B and p govern the shape of the relationship of effort to count, and are estimable from CBC data. For $p < 0$, the model specifies diminishing returns as effort increases. Analysts often assume that counts increase proportionally to the effort expended (Caffrey and Peterson 2003). With only finitely many birds to be counted, and no limit to the amount of effort that could be expended in counting them, this assumption strikes us as unreasonable. The assumption can be formally tested in the context of Link and Sauer's model, which includes it as a special case: setting $B = 1$, as p approaches zero the limit of $f(\xi)$ is simply ξ, so that the expected count is proportional to effort.

For fixed values of the parameter p, Link and Sauer's (1999a, 1999b) model is a loglinear model. They therefore proposed the use of standard loglinear model-fitting techniques, carried out repeatedly over a grid of values of p, and selecting the value of p that maximized the likelihood. This procedure is reasonable and effective for the analysis of CBC data at local scales, but impractical for large scales of analysis.

For the CBC, analysis has traditionally been conducted at the level of physiographic strata, relying on these strata to impose consistency in sampling intensity and to limit the consequences of nonrandom site selection (Link and Sauer 1999a, 1999b, Sauer and Link 2002a). However, regional analysis of CBC data presents significant analytical challenges. As the survey covers a large portion of North America, aggregation of information over space must accommodate the regional variation in number of samples and precision of estimation. Historically, methods of analysis for data from regional surveys such as the CBC and the North American Breeding Bird Survey (BBS) have either failed to accommodate this regional variation or have used relatively cumbersome methods such as route-regression or empirical Bayes (Link and Sauer 1998, 1999b).

Link and Sauer (2002) recently proposed a hierarchical model for analysis of BBS data. Here, we describe a similar model for CBC data, modified to incorporate the effort model described above. Unlike earlier models for CBC data, the hierarchical model permits region-specific effort effects and regional rather than local modeling of population change. The model presented is easily modified to incorporate additional covariates that might influence either counting efficiency or population size. Although the analysis of such models is computationally intensive, it can be conducted using readily available software, allowing conservationists to fully exploit the CBC for analysis of population change at multiple geographic scales. As an example, we estimate population change for the American Black Duck (*Anas rubripes*) using CBC data and compare our results with the Midwinter Waterfowl Inventory (MWI; Conroy et al. 1988) a survey historically used to monitor American Black Ducks. Where the ranges of the surveys overlap, CBC and MWI are in broad agreement. However, CBC data have larger geographic coverage, and provide information about the entire population at a larger geographic scale.

METHODS

HIERARCHICAL MODEL

We treat CBC counts as overdispersed Poisson random variables, with means described by a loglinear regression with random effects. The count taken in stratum i, circle j, and year t is denoted by $Y_{i,j,t}$, with mean $\lambda_{i,j,t}$ satisfying

$$\log(\lambda_{i,j,t}) = S_i + \omega_j + \gamma_{i,t} + \beta_i (t - t^*)$$
$$+ B_i(\xi_{i,j,t}{}^{p_i} - 1)/p_i + \varepsilon_{i,j,t} .$$

Thus, stratum-specific intercept (S_i) and site effects (ω_j) are modeled as additive on the log scale. Temporal change is modeled by stratum-specific loglinear change with coefficient β_i and by year effects $\gamma_{i,t}$; change is indexed relative to a base year t^*. The model includes a stratum-specific effect of effort $B_i (\xi_{i,j,t}{}^{p_i} - 1)/p_i$; as previously described; this feature of the analysis stands in contrast to earlier analyses in which only a single effect of effort was modeled for the entire area over which a species occurred (Link and Sauer 1999b). We note that the effort values are scaled to an overall mean, so that if the effort expended in producing count $Y_{i,j,t}$ is equal to the overall mean, then $\xi_{i,j,t} = 1$, and the effort effect is zero. Finally, the model includes overdispersion effects ($\varepsilon_{i,j,t}$) allowing for lack of fit to the Poisson model, which otherwise imposes a strict relation equating mean and variance.

The model is hierarchical in that most of the effects are treated as random variables. Circle effects, year effects, overdispersion effects, and parameters describing effort effects are all treated as independent normally distributed random variables. The means of the normal distributions are all zero, except for the distribution of the effort parameters p_i and B_i, which have means μ_p and μ_B. Variances are denoted by σ^2 with a single identifying subscript (such as σ_ω^2 for the variance among circles). The only exception is the year effects, for which the variance is allowed to vary among strata: the variance for year effects in stratum i is $\sigma_{\gamma i}^2$. The variances, the means μ_p and μ_B, the coefficients of temporal change β_i, and the stratum effects S_i are all fixed effects.

SUMMARY ANALYSES

Count survey data are not censuses; population sizes remain unknown. Thus, annual indices and population trends must be defined in terms of model parameters (Link and Sauer 2002). Our annual index for stratum i includes all of the stratum-level effects for counts, with adjustments A_i for the area of the stratum relative to the area covered by CBC circles, and an adjustment z_i for the proportion of circles in which the species occurs. Our index to population size in stratum i at time t is

$$N_{i,t} = A_i z_i \exp(S_i + \beta_i(t - t^*) + \gamma_{i,t}) .$$

Trend for stratum i between times t_a and t_b is defined as the geometric mean rate of change in $N_{i,t}$ over the interval, i.e., as

$$T_i = \left\{ \frac{N_{i,t_b}}{N_{i,t_a}} \right\}^{\frac{1}{t_b - t_a}}$$

To summarize population change over a collection of strata, we simply define composite indices

$$N_t = \sum_{i=1}^{I} N_{i,t} ;$$

trend is once again defined as the geometric mean rate of change in the index.

Stratum-level summaries are commonly scaled to numbers of birds per circle. For such purposes we use indices $n_{i,t} = N_{i,t}/A_i$.

ESTIMATION FOR HIERARCHICAL MODELS

We fit hierarchical models using Bayesian methods. Bayesian methods are well suited for hierarchical models, as all parameters are treated as random variables. Fortunately, the formidable technical difficulties that traditionally limited Bayesian analyses have been mitigated by Markov chain Monte Carlo techniques (MCMC; Gilks et al.1996). In MCMC, probability distributions are simulated by drawing dependent random samples from the distributions, and features of the samples are used to approximate the features of the probability distributions. Link and Sauer (2002) provide a discussion of the use of MCMC for Bayesian approaches to fitting hierarchical models.

Bayesian inference is based on the distribution of the parameters conditional on the data (the posterior distribution), which is calculated by scaling the product of the sampling distribution of the data and prior distributions of the parameters. We used standard noninformative priors (Gilks et al. 1996): reciprocals of variances were assigned gamma distributions with mean = 1 and variance = 1000; parameters β_i, S_i, and μ_B were assigned mean zero normal distributions, with variance = 1000^2. We used a uniform prior on the interval $[-4, 4]$ for μ_p, because previous experience indicated that $|p|$ seldom exceeds 2.0.

The mean (or median) of the posterior distribution is used as a point estimate; interval

estimates can be constructed using percentiles of the posterior distribution. For example, the interval extending from the 2.5th to 97.5th percentiles is often referred to as a 95% credible interval in analogy to frequentist confidence intervals. We use the abbreviation CI for credible intervals.

Ghosh (1992) noted that collections of posterior means are underdispersed relative to the collection of true parameters. Consequently, plots of posterior mean annual indices tend to understate the variability in population change. We therefore suggest that graphical displays of annual indices should be made using constrained Bayes estimates, in which year effects are rescaled to better portray temporal patterns of variation (Link and Sauer 2002). This rescaling is accomplished by inflating the variance of the posterior distribution of year effects by a factor

$$c = \frac{Posterior\ mean\ of\ temporal\ variance}{Variance\ of\ mean\ year\ effects} \ .$$

These inflation factors are only for graphical display of variation over time in the indices; the posterior means of annual indices remain the best mean squared error estimates of individual values and are summarized in the results.

Recalling that the expedient of scaling counts by effort is only justified if $p = 0$ and $B = 1$, it is of interest to evaluate the location of the point $(0, 1)$ in the posterior distribution of pairs (p, B). We thus considered the distance from sampled values (p, B) to the "center" of the posterior distribution, i.e., the posterior mean $(p*, B*)$, asking what proportion of the posterior distribution lies at a greater distance from the center than the point $(0, 1)$. That is, we computed

$$d(p,B) = \sqrt{(p - p*)^2 + (B - B*)^2}$$

for each sampled pair (p, B), and computed the posterior probability that $d(p, B) > d(0, 1)$. This probability is a Bayesian p-value (Gelman et al. 2004) for testing the adequacy of the usual effort adjustment.

MARKOV CHAIN MONTE CARLO SIMULATIONS

We used program WinBUGS (Spiegelhalter et al. 1999, available for free download at http://www.mrc-bsu.cam.ac.uk/bugs/ [14 November 2005]) to sample the posterior distributions of parameters and indices. We generated chains of length 10 000, discarding the first 4000 as a burn-in (see Link et al. 2002 for a simple introduction to MCMC and our Discussion for some comments on the length of chains used in MCMC calculations). Features of the posterior distributions were estimated from the remaining observations.

ANALYSIS OF AMERICAN BLACK DUCKS

American Black Ducks have traditionally been an important harvested species in eastern North America. American Black Duck populations are thought to have started to decline in the 1950s, and a variety of monitoring and management activities have been initiated to better monitor and conserve the species (Conroy et al. 2002). Although breeding surveys have recently been implemented in eastern Canada and the northeastern United States, most historical information about the species is based on surveys of wintering populations such as the Midwinter Inventory (MWI). The CBC has been used as a supplemental source of information on American Black Duck populations, for example, Butcher and McCulloch (1990) estimated rates of change in American Black Duck populations in their analysis of count-effort associations in CBC data, but no comprehensive analysis of regional patterns of population change has been conducted for the species. In contrast to the MWI, the CBC is not limited to the United States; the CBC thus provides unique information for the American Black Duck, some populations of which winter in southern Canada. It is therefore of interest to use CBC data both to assess the consistency of CBC and MWI results for comparable areas and to evaluate change of American Black Duck populations not surveyed by the MWI.

We used the hierarchical model to estimate population change of wintering American Black Ducks for the interval 1966–2003 using CBC data. Following the National Audubon Society convention, we identified the year of a count by the calendar year following the Christmas period in which the count was conducted. Earlier analyses categorized CBC circles into physiographic strata developed for BBS analysis (Bystrak 1981), but in this analysis we chose to use Bird Conservation Regions (BCRs) as strata for analyses. BCRs were

developed for regional avian conservation, and are based on ecoregions defined by the Commission for Environmental Cooperation (1997). Sauer et al. (2003) analyzed BBS data using BCRs. Following the convention of earlier analyses (Dunn and Sauer 1997), we excluded poorly sampled strata (Boreal Taiga Plains; Taiga Shield and Hudson Plains; and Boreal Softwood Shield) in northern Canada.

The large size of most BCRs creates an important logistical issue for analysis, as most species are distributed throughout several BCRs but are only found on the margins of many other BCRs. The analyst must decide which strata to include in analyses, and consideration must be given to the consequences of including peripheral BCRs. Often, the large areas of peripheral BCRs make them an influential component of the analysis, even though the species is not found in most of the BCR. To address this, we conducted three analyses. In the first, we classified BCRs as within the winter range of American Black Ducks if the species was seen on >4 circles during the study interval. American Black Ducks have been encountered in 18 circles in the Northern Pacific Rainforest, however these observations represent released birds and incidental observations (G. LeBaron, National Audubon Society, pers. comm.), so we chose not to include them in this analysis. We conducted two additional analyses to address the effects of choice of strata: (1) an analysis of 11 core strata where American Black Ducks routinely wintered across the geographic range of the stratum; and (2) an analysis which in which strata were defined as the intersection of BCRs with states or provinces. In the latter, we only included strata that contained >4 circles in which wintering American Black Ducks were encountered. Analysis of the data by BCRs within states and provinces is appealing because it permits aggregation to the state and province level as well as to the level of BCRs. It also effectively limits the influence of peripheral strata by excluding portions of the BCRs that fall into states or provinces in which the species was not encountered. However, data are often sparse within these smaller strata, leading to very imprecise estimates.

Categorizing effort can also be problematic in CBC analyses because of missing data and inconsistent recording and summary of effort.

Following other recent analyses, we used total party-hours as a measure of counting effort (Butcher and McCulloch 1990, Link and Sauer 1999a, 1999b). A party-hour is the number of hours spent by a group in the field, excluding counts conducted at feeders. The covariate ξ used in the analysis is defined as the number of party-hours scaled by the overall survey mean.

Lastly, we compared the CBC results to the MWI results for American Black Ducks. In the MWI, states are divided into sample units, and waterfowl are counted in the units using a variety of sampling approaches (primarily counts from fixed-wing aircraft, although ground counts, counts from boats, and other methods are also used; see review by Eggeman and Johnson 1989). MWI data and metadata are available from the US Fish and Wildlife Service (http://birddata.fws.gov/databases/mwi/aboutmwi.htm [14 November 2005]). In our comparative analysis, we used total counts from the MWI for American Black Ducks from 1966–2003. Because the MWI does not cover Canada, we analyzed CBC data for the United States only, at the scale of BCRs within states, and aggregated these units to obtain composite population indices for comparison with MWI data. We also plotted the composite analysis for the entire CBC survey area. For presentation, we scaled each of these time series by subtracting their means and dividing by their standard deviation.

RESULTS

The primary analysis included data from 18 BCRs (Table 1). Within these BCRs, the proportion of circles containing American Black Ducks and the mean counting effort varied greatly (Table 1). Many BCRs that are peripheral to the American Black Duck wintering range were included in the analysis, including the Shortgrass Prairie (five circles with data, proportion of sites with data = 0.08) and the Oaks and Prairies (nine circles, proportion = 0.19). In the center of the wintering range, American Black Ducks were seen on 99% of circles in the New England/Mid-Atlantic Coast and on >80% of circles in five other BCRs. Some very large BCRs such as the Prairie Potholes had few circles containing American Black Ducks (21 circles, proportion = 0.17, area = 1916.7 circles). Effort also varied widely among and within BCRs, with some BCRs

TABLE 1. Number of Christmas Bird Count circles (C), number of circles containing American Black Ducks (C_d), proportion of circles containing American Black Ducks (C_d/C), area (number of Christmas Bird Count circles in a region), effort (median hours of counting by parties of counters scaled by mean of all party hours used in analysis, with 2.5[th] and 97.5[th] percentiles), and abundance index (count per mean effort, predicted for the midyear of the survey interval [1982]: posterior median and 95% credible interval [CI]) summarized at the scale of Bird Conservation Regions for counts conducted during 1966–2003.

Bird Conservation Region	C	C_d	C_d/C	Area	Effort (Median, 95% range)	Abundance (95% CI)
Prairie Potholes	127	21	0.17	1916.7	0.49 (0.13–2.90)	0.02 (0.00–0.08)
Boreal Hardwood Transition	138	61	0.44	1350.1	0.58 (0.13–1.49)	0.64 (0.33–1.33)
Lower Great Lakes/St. Lawrence Plain	194	179	0.92	437.1	0.93 (0.36–2.46)	12.97 (8.91–18.77)
Atlantic Northern Forest	163	150	0.92	796.5	0.61 (0.17–1.41)	28.64 (18.86–46.60)
Shortgrass Prairie	62	5	0.08	840.9	0.60 (0.13–3.45)	0.00 (0.00–0.04)
Central Mixed Grass Prairie	67	10	0.15	868.4	0.45 (0.13–1.37)	0.01 (0.00–0.10)
Oaks and Prairies	47	9	0.19	424.3	0.87 (0.25–2.27)	0.01 (0.00–0.09)
Eastern Tallgrass Prairie	240	182	0.76	1171.0	0.63 (0.19–1.64)	3.98 (2.68–5.95)
Prairie Hardwood Transition	146	104	0.71	503.0	0.69 (0.14–1.86)	3.63 (2.42–6.06)
Central Hardwoods	102	77	0.75	661.8	0.69 (0.22–1.44)	14.67 (7.64–28.04)
West Gulf Coastal Plain/Ouachitas	53	11	0.21	466.3	0.69 (0.20–1.42)	0.05 (0.00–0.42)
Mississippi Alluvial Valley	45	25	0.56	250.2	0.65 (0.14–1.51)	0.55 (0.17–1.93)
Southeastern Coastal Plain	132	109	0.83	1085.1	0.81 (0.28–1.86)	5.04 (3.04–8.47)
Appalachian Mountains	228	191	0.84	932.1	0.76 (0.25–1.92)	6.15 (4.09–9.05)
Piedmont	104	93	0.89	408.3	1.08 (0.36–2.76)	10.04 (6.28–16.78)
New England/ Mid-Atlantic Coast	158	156	0.99	164.9	1.26 (0.38–3.23)	225.10 (153.80–328.90)
Peninsular Florida	75	34	0.45	205.6	1.39 (0.53–2.62)	0.05 (0.02–0.13)
Gulf Coastal Prairie	61	20	0.33	152.1	1.02 (0.35–5.03)	0.08 (0.02–0.33)

showing a scaled mean effort below 0.5, indicating that their median effort was less than half of the average effort value from all circles (Table 1). In contrast, some circles had extremely large amounts of effort (>5 times the average).

ESTIMATES OF EFFORT COEFFICIENTS AND EXPONENTS

Estimates of p ranged from -0.42 to 0.03, although the 95% CI overlapped 0.0 in 13 of the 18 BCRs (Table 2). Estimates of the coefficient B ranged from 0.47 to 1.02; only two estimates had CIs that overlapped 0.0. For most BCRs, $d(p, B)$ tended to be less extreme than $d(0, 1)$, indicating that the common expedient of simply scaling counts by effort is inadequate. BCRs that had weaker evidence for effort effects (e.g., Peninsular Florida, where the proportion of occupied circles $= 0.724$) tended to be areas in

which American Black Ducks are rare (Table 2). For each value of p and B, the effect of effort can be displayed by plotting $f(\xi) = \exp(B (\xi^p - 1)/p)$. Plots of estimated effort effects show variation among BCRs that could have substantial effects on counts, especially at higher effort levels (Fig. 1).

POPULATION INDICES AND TREND ESTIMATES

The BCRs differed greatly in abundance of American Black Ducks. Circles in the New England/Mid-Atlantic Coast BCR had by far the highest abundances of American Black Ducks per circle (Table 1). There were also distinct regional patterns in population change. Northeastern strata showed generally increasing populations (Fig. 2a). These increases are summarized by trend estimates that all indicate increasing populations (estimated trends are

TABLE 2. Estimated effort and population change coefficients (posterior medians) and 95% credible intervals (CI = 2.5th percentile–97.5th percentile) for a hierarchical model of American Black Ducks using Christmas Bird Count data from 1966–2003. Estimates of parameters p and B governing the effort ($>$) relationship ($\exp(B(>^p-1)/p)$) and trend estimates are presented for Bird Conservation Regions. The Bayesian p-value for testing the assumption that $p = 0$ and $B = 1$ is also presented for each Bird Conservation Region.

Bird Conservation Region	p	B	Trend (% per year)	p-value for effort
Prairie Potholes	−0.20 (−0.52, 0.21)	0.68 (0.32, 1.13)	−0.43 (–4.82, 3.40)	0.14
Boreal Hardwood Transition	−0.09 (−0.41, 0.51)	0.51 (0.24, 0.81)	4.30 (2.40, 6.30)	0.07
Lower Great Lakes/ St. Lawrence Plain	−0.37 (−0.60, −0.19)	0.76 (0.63, 0.88)	1.90 (0.90, 2.80)	<0.001
Atlantic Northern Forest	0.03 (−0.24, 0.42)	0.53 (0.34, 0.72)	3.10 (1.80, 4.40)	0.01
Shortgrass Prairie	−0.21 (−0.61, 0.25)	0.65 (0.18, 1.04)	−7.26 (–20.99, 2.50)	0.14
Central Mixed Grass Prairie	−0.15 (−0.47, 0.43)	0.59 (0.09, 0.97)	−9.82 (–19.93, −0.71)	0.13
Oaks and Prairies	−0.23 (−0.59, 0.22)	0.56 (−0.01, 0.94)	−8.53 (–20.32, 2.20)	0.08
Eastern Tallgrass Prairie	−0.21 (−0.42, −0.01)	0.63 (0.48, 0.78)	−2.51 (–3.61, –1.43)	<0.001
Prairie Hardwood Transition	−0.17 (−0.42, 0.11)	0.54 (0.36, 0.74)	−0.38 (–1.25, 0.60)	0.001
Central Hardwoods	−0.13 (−0.37, 0.19)	0.75 (0.54, 0.98)	–3.47 (–5.10, –1.88)	0.12
West Gulf Coastal Plain/Ouachitas	−0.16 (−0.51, 0.40)	0.56 (−0.03, 0.94)	−9.48 (–24.92, 3.50)	0.12
Mississippi Alluvial Valley	−0.31 (−0.64, 0.02)	0.75 (0.50, 1.08)	−4.96 (–7.79, –1.98)	0.06
Southeastern Coastal Plain	−0.24 (−0.54, 0.09)	0.47 (0.28, 0.66)	−6.03 (–7.43, –4.70)	0.002
Appalachian Mountains	−0.42 (−0.62, −0.22)	0.80 (0.65, 0.96)	−0.65 (–1.65, 0.40)	<0.001
Piedmont	−0.27 (−0.52, −0.04)	1.02 (0.79, 1.24)	–1.36 (–2.41, −0.10)	0.08
New England/Mid- Atlantic Coast	−0.24 (−0.40, −0.08)	0.82 (0.70, 0.95)	−0.46 (–1.02, 0.10)	<0.001
Peninsular Florida	−0.24 (−0.70, 0.20)	0.81 (0.49, 1.21)	–7.31 (–9.14, –5.45)	0.28
Gulf Coastal Prairie	−0.29 (−0.73, 0.09)	0.62 (0.19, −0.95)	–13.9 (–21.63, –7.48)	0.05
Overall			−0.14 (−0.67, 0.40)	

$>$0, and 95% CIs do not overlap zero for any of the strata; Table 2). The important New England/Mid-Atlantic Coast BCR showed a slight decline (Fig. 2b), although the estimated trend of $−0.46\%$ yr^{-1} was not statistically significant (95% CI: −1.02, 0.1, Table 2). Mid-Atlantic and southeastern populations showed declines (Fig. 2c) that ranged from $−7.31\%$ yr^{-1} to $−0.65\%$ yr^{-1}. Other BCRs peripheral to the winter range of American Black Ducks also tended to show population declines, most notably the Central Hardwoods BCR ($−3.47\%$ yr^{-1}, Fig. 2d). Trend estimates (posterior medians) from these regions are all negative, although some are quite imprecise (e.g., Shortgrass Prairie). Composite population indices summarizing data from all 18 BCRs (Fig. 3) provide an aggregate view of population change, and display a generally stable population level over the 1966–2003 interval (1966–2003 trend estimate $−0.14\%$ yr^{-1} [95% CI: −0.67, 0.4]).

Removal of peripheral strata from the analysis resulted in a composite time series based on 11 strata that is very similar to the composite series based on 18 strata in terms of estimated year-to-year changes, but is scaled to a higher abundance (Fig. 3). The stratum-level analysis is scaled to an even larger abundance, and is less precise than the analyses based on larger areas, reflecting the imprecision associated with smaller sample sizes within smaller areas.

COMPARISON OF CBC WITH MWI RESULTS

The CBC and MWI results show consistent overall patterns, although year-to-year changes are often not coincident (Fig. 4). The trend
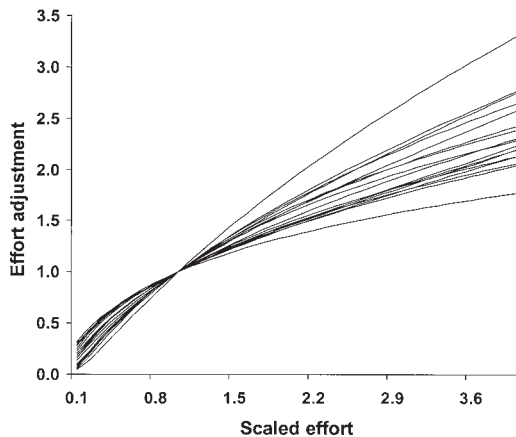
FIGURE 1. Proportional amount of adjustment for effort as a function of scaled effort (party-hours of counting on CBC circle scaled to mean party-hours for all circle-years) by bird conservation region. These curves reflect the effect of effort on counts, and show how it differs among strata. The bird conservation region curves listed from highest to lowest by magnitude of effort adjustment at highest effort value are: Piedmont, Peninsular Florida, Central Hardwoods, New England/Mid-Atlantic Coast, Prairie Potholes, Mississippi Alluvial Valley, Appalachian Mountains, Shortgrass Prairie, Lower Great Lakes/St. Lawrence Plain, Atlantic Northern Forest, Central Mixed Grass Prairie, West Gulf Coastal Plain/Ouachitas, Eastern Tallgrass Prairie, Boreal Hardwood Transition, Gulf Coast Prairie, Prairie Hardwood Transition, Oaks and Prairies, and Southeastern Coastal Plain.

estimate from the CBC for the United States is -1.21% yr^{-1}(95% CI: -2.27, -0.60), while the comparable estimate from the MWI is -1.59% yr^{-1}. Composite results for the entire CBC survey area including southern Canada show a smaller decline (-0.14% yr^{-1}), and indicate some high (although imprecise) annual indices in the period 1999–2003.

DISCUSSION

HIERARCHICAL MODELS AND THE CBC

The hierarchical model we present for analysis of CBC data has several advantages over alternative approaches. It allows for direct estimation of year effects while controlling for nuisance covariates (e.g., effort) that influence counts. It also permits modeling the effects of environmental factors that may influence both population change and spatial variation in abundance. The hierarchical approach to estimation of effort effects allows for re-

gional variation in the shape of the effort adjustment while accommodating the large differences in precision of estimates among regions. In the model, composite regional indices and trends are derived parameters, and Markov chain Monte Carlo (MCMC) simulations allow the direct estimation of a variety of additional derived quantities such as area importance scores (Carter et al. 2000) and population stability metrics (Sauer and Link 2002b). Further, as noted by one reviewer, "the Bayesian framework is useful for exploring alternative latent biological and sampling mechanisms that give rise to the counts."

There is no absolute standard for the length of chains to be generated in conducting Markov chain Monte Carlo analyses. The burn-in period of 4000 and chain length of 10 000 used here are short, however we examined plots of autocorrelations and ran multiple chains with diffuse starting values and found satisfactory indication of stationarity and convergence. MCMC is for many analysts a somewhat new tool, and care must be used in its application. This, of course, is true even of familiar approaches such as numerical maximum likelihood, in which the possibilities of noncovergence or convergence to local maxima are genuine concerns.

Effort adjustments are a critical component of any CBC analysis, and the hierarchical modeling of p and B is an important extension of earlier work that required repeated fitting of a loglinear model and comparisons of deviances to determine the optimal p (Link and Sauer 1999b). The hierarchical model fits the parameters directly, and allows for regional variation in parameters. The MCMC analysis also provide the basis for evaluating whether $p = 0$ and $B = 1$.

We chose to model p hierarchically; alternatively, we could have used noninformative priors on the ps and Bs and estimated these parameters without the influence of group structure. We prefer the hierarchical form, as it accommodates regional variation in precision of estimates. We view our parameterization of effort as a starting point for more extensive evaluations of the influence of effort on counts, as CBC observers record several different types of effort. One generalization of this approach would be to simultaneously consider the effects
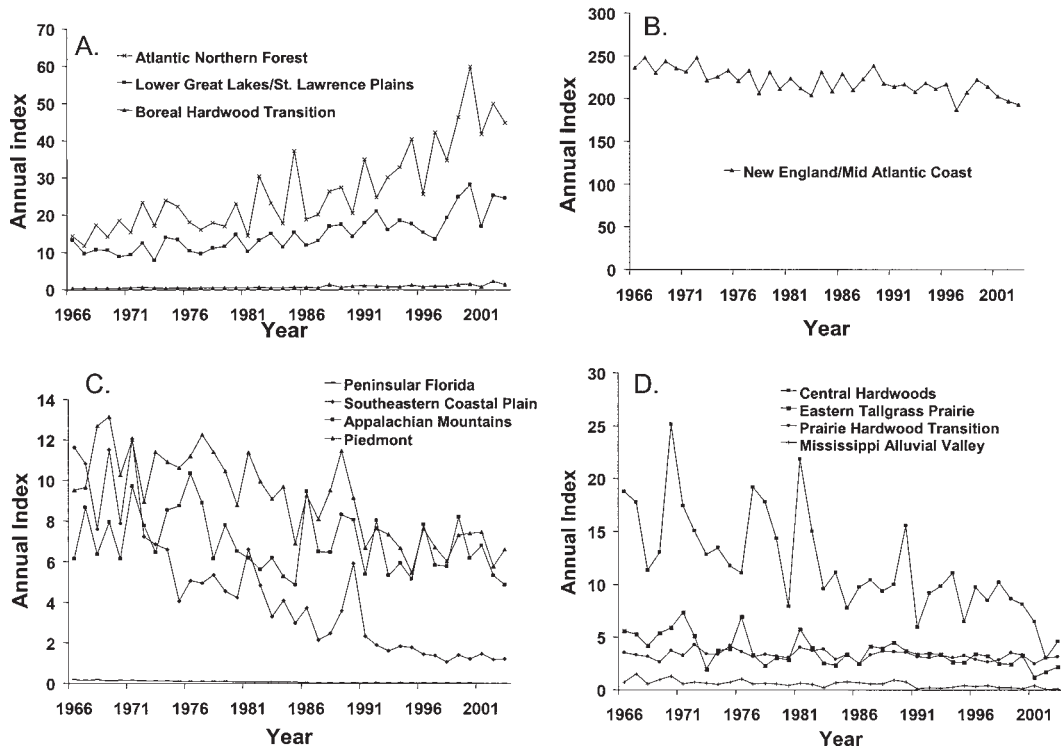
FIGURE 2.   Christmas Bird Count annual indices of American Black Duck abundance derived from the hierarchical model analysis for years 1966–2003 for (A) northeastern bird conservation regions: Boreal Hardwood Transition, Lower Great Lakes/St. Lawrence Plain, and Atlantic Northern Forest; (B) New England/Mid-Atlantic Coast; (C) southeastern regions: Southeastern Coastal Plain, Appalachian Mountains, Piedmont, and Peninsular Florida; and (D) selected peripheral bird conservation regions: Eastern Tallgrass Prairie, Prairie Hardwood Transition, Central Hardwoods, and Mississippi Alluvial Valley.

of different types of effort that could have differing influences on CBC counts.

Any geographic summary of CBC data must in some way accommodate regional variation in populations. In our analysis, we have followed the convention of weighting local estimates by area to estimate population-level parameters. For the CBC, this area weighting is problematic due to the nonrandom selection of sites (Sauer and Link 2002a). More realistic weighting could be achieved by developing model-based weights, which would more accurately reflect how well the CBC circles represent regional populations. Use of strata (such as BCRs) provides a reasonable starting point for this modeling (Sauer and Link 2002a). However, most species are found only peripherally in some BCRs, and estimation of total population size is complicated by inclusion of strata with very limited data for a species. Our empirical evaluation of this issue by excluding peripheral

BCRs suggested that for American Black Ducks total population estimates were not greatly influenced by the inclusion of these data, although the low abundances in these areas tended to affect the scaling of the composite population indices. We suggest that investigators applying these methods be cautious when summarizing analyses over BCRs with limited data, and consider the influence of peripheral strata on the analysis.

We also note that while hierarchical approaches provide great analytical flexibility when data are limited, there are temporal and spatial patterns in the quality of CBC data that must be considered. It is well known that CBC participation and coverage have increased over time, and some regions have very limited data before the 1970s. We recommend screening the data and aggregating regions to prevent estimation based on strata that do not contain data from the initial years of the survey. The
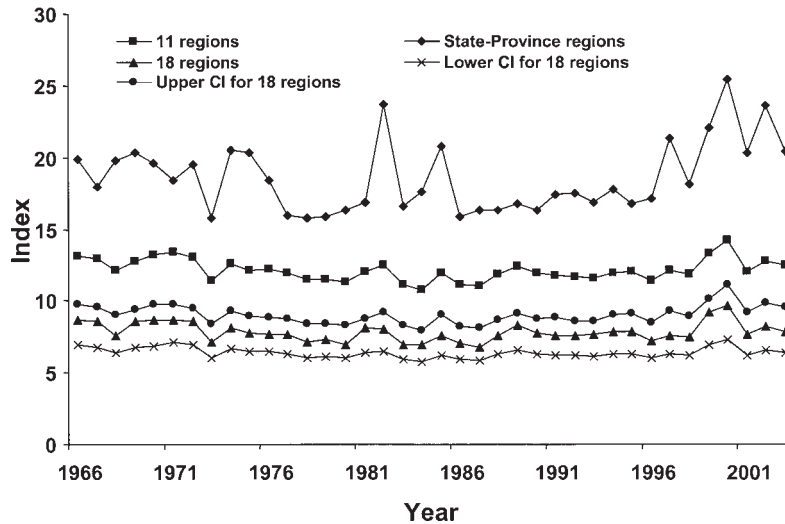
FIGURE 3. Annual indices for American Black Ducks from the Christmas Bird Count data based on three alternative analyses: an analysis using 18 bird conservation regions with associated credible intervals, an analysis based on 11 bird conservation regions from the core of the wintering range of the species, and an analysis based on strata composed of bird conservation regions within state and province areas.

approaches presented here estimate interval-specific trend as a ratio of the year effects for the first and last years of the interval, and therefore tend to be influenced by missing data in these years. If data are not available from these years, then trend can be redefined to conform to a period for which data exist.

AMERICAN BLACK DUCK ANALYSES

Regional patterns of population change for American Black Ducks documented using CBC data provide some important insights into the population dynamics of the species. Regional patterns of population change are evident, with declines of populations in the southern and
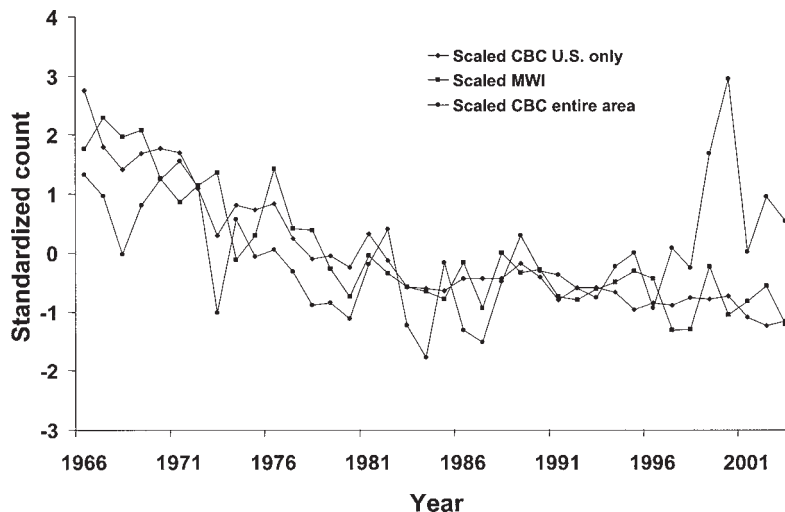

FIGURE 4. Comparison of annual indices of American Black Duck populations for the United States from 1966–2003, based on Christmas Bird Count and Midwinter Inventory data, and the annual indices for the entire Christmas Bird Count area including southern Canada. Indices are scaled for comparison by standardizing each value by subtracting the mean of each time series and dividing by the standard errors.

central portions of the wintering range and more stable populations in the northeastern portions of the range. American Black Duck breeding ranges have been contracting across the Boreal Hardwood Transition and Lower Great Lakes/St. Lawrence Plain BCRs throughout the last half of the 20th century, and band recovery data suggest that ducks banded in the western parts of these BCRs historically comprised the majority of American Black Ducks that wintered in the southeastern United States (Pendleton and Sauer 1992). However, hunting, habitat change on breeding and wintering areas, and hybridization or competition with Mallards (*Anas platyrhynchos*) have all been suggested as possible causes of regional declines in American Black Duck populations (Conroy et al. 2002), and patterns of population change in wintering areas do not by themselves provide definitive information on the cause of population change. CBC data provide a large amount of site-specific geographic information on population change, and the hierarchical model described here can be used in conjunction with geographical covariates such as habitat change to further our understanding of factors associated with population change.

The CBC also provides extensive data from regions not covered by other winter surveys. For American Black Ducks, the CBC and MWI showed similar patterns of population change at the scale of the United States, but additional information from the CBC in southern Canada increased our understanding of range-wide patterns of population change. Documentation of long-term declines of American Black Ducks has been based primarily on MWI data, and while consistent patterns among indices does not necessarily confirm results (Sauer et al. 1994), it does tend to enhance the credibility of surveys. In addition, as the MWI does not count American Black Ducks in southern Canada, and has been criticized for inconsistencies in methods (Eggeman and Johnson 1989), comparative analysis with CBC data can assist in interpretation of MWI data and provide documentation of population change in the northern portions of the species' wintering range.

ACKNOWLEDGMENTS

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